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The distance modulus of the Large Magellanic Cloud:

Constraints from RR Lyrae pulsation properties

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Abstract. It has recently been suggested that the discrepancy between the "long" and "short" distance moduli of the Large Magellanic Cloud (LMC), as inferred from the properties of the Cepheid and RR Lyrae variables, respectively, might be due to the action of "third parameters" between the Galaxy and the LMC, which would make the RR Lyraes in the old LMC globular clusters brighter than their Galactic counterparts by $\simeq 0.3$ mag. Through analysis of the RR Lyrae pulsation properties, we show that this idea is not supported by the available data. A satisfactory explanation of the problem has yet to be found.

Key words: Stars: evolution – Stars: horizontal branch – Stars: variables: other – Galaxies: distances and redshifts – *(Galaxies:)* Magellanic Clouds

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1. Introduction

In an important *Letter*, Walker (1992b) has called attention to what appeared to be a fundamental problem with our knowledge of the properties of the RR Lyrae stars: the Baade-Wesselink (BW) calibration of the RR Lyrae absolute magnitude-metallicity relation (e.g., Carney et al. 1992; see also Storm et al. 1994 for a recent discussion and a comparison between field and cluster results) was shown by him to give a distance modulus for the Large Magellanic Cloud (LMC) that is substantially shorter than indicated by the LMC Cepheids (e.g., Laney & Stobie 1994) and by the properties of the SN1987A circumstellar envelope (e.g., Crotts et al. 1995). The difference was attributed to a problem in the zero point of the $M_V(\mathrm{RR}) - [\mathrm{Fe/H}]$ relation: RR Lyrae stars would thus be brighter by $\simeq 0.3$ mag than indicated by the BW method. Among the implications of this result stand out a reduction in the ages of globular clusters (GCs) and a decrease in the value of the Hubble parameter H_0 (van den Bergh 1995 and references therein).

Independent evidence that the RR Lyrae variables should be brighter than suggested by the BW method has been presented by Saha et al. (1992), Catelan (1992), Simon & Clement (1993), Cacciari & Bruzzi (1993), Sandage (1993), Dorman (1993), Fernley (1994), Silbermann & Smith (1995), etc. Castellani & De Santis (1994) have shown that the BW luminosities cannot be reconciled with the standard models for evolution on the horizontal branch (HB), unless the helium abundance Y is lower than 20% by mass, and questioned the accuracy of BW analyses. Bono & Stellingwerf (1994), Bono et al. (1994) and Fernley (1994) have similarly argued that some of the basic assumptions of the BW method may be in error. On the other hand, the latest analyses of statistical parallaxes of Galactic field halo stars (Layden et al. 1994) have reportedly given some support to the BW results.

An explanation different from Walker's (1992b) has been proposed by van den Bergh (1995), according to whom the suggested discrepancy between the distance moduli of the LMC that are inferred through analysis of the Cepheid and RR Lyrae variables may *not* necessarily imply that the BW absolute magnitudes are incorrect, but rather that a "third parameter" is acting in the LMC in such a way as to make the LMC RR Lyraes intrinsically brighter than those in the Galaxy by $\simeq 0.3$ mag.

Indeed, the old LMC GCs are somewhat shifted toward redder HB types in the HB morphology$-$[Fe/H] plane. This has often been interpreted (e.g., Walker 1992c) as evidence that the old LMC GCs are younger by a few Gyr than

the Galactic globulars. We note, in passing, that the very metal-poor Galactic GCs which do not have extremely blue HB types (e.g., M15 and M68) have *not* generally been associated to a younger component of the Galactic halo (e.g., van den Bergh 1993; Zinn 1993), as would be required in the age interpretation of the second-parameter phenomenon.

In the present *Letter*, we submit van den Bergh's (1995) suggestion to the critical analysis that is enabled by the extensive surveys of RR Lyrae pulsation properties in the LMC GCs by Walker (1989, 1990, 1992a,c).

2. Expected trends in second-parameter candidates

From the location of the old LMC GCs on the HB morphology-metallicity plane (see, e.g., Fig. 1 in Catelan & de Freitas Pacheco 1993), several possibilities emerge for the sense of variation in the known second-parameter candidates: a *younger age*; a *smaller amount of mass lost during the red giant branch (RGB) phase*; a *lower* Y; a *lower helium-core mass at the helium flash* ($M_{\rm c}$); or a *higher relative abundance of the* α*-capture elements*. These trends are well known from studies of the evolution of HB stars (e.g., Sweigart & Gross 1976). The trend of variation of the HB morphology with [α/Fe] was inferred from the analysis of Salaris et al. (1993). Quantitative estimates of the required changes in these candidates are, unfortunately, difficult to obtain (Catelan & de Freitas Pacheco 1993).

– *Age*: the primary effect of age variations is upon the masses attained by HB stars. As far as the absolute magnitudes of the RR Lyrae variables are concerned, age changes are essentially irrelevant. Thus, the age interpretation of the second-parameter phenomenon would not naturally produce brighter HBs in the LMC;

– *Mass loss on the RGB*: like age, mass loss by stellar winds from the envelopes of RGB stars acts only to reduce the expected masses on the HB phase, and has but little impact upon RR Lyrae luminosities;

– *Helium abundance*: a higher Y in HB stars would produce brighter RR Lyrae variables in the LMC, in comparison with the Galactic ones, but also bluer HB types;

– *Helium-core mass*: a higher $M_{\rm c}$ in the LMC, in comparison with the Galactic values, might originate, for instance, in higher stellar rotation rates (see discussion and references in Catelan et al. 1996). This would produce brighter RR Lyrae variables, but would also lead to bluer HB morphologies;

– *Abundances of the* α*-elements*: since an overabundance of the α-elements may, in a first approximation, be interpreted in terms of a higher metallicity Z for a given [Fe/H] ratio, it follows that a smaller [α/Fe] ratio might account for a brighter HB in the LMC. It may be noted that existing chemical evolution models (cf. Fig. 4 in Matteucci & Brocato 1990) suggest that, at low metallicities, [α/Fe] may be lower in the LMC than in the Galaxy. Observational element ratios at the low metallicities that characterize LMC GCs are badly needed. However, a smaller [α/Fe] ratio would also lead to bluer HBs.

To be sure, there are possible combinations of variations in these parameters that could account for brighter RR Lyraes and redder HB types simultaneously. It is conceivable, for instance, that a higher $M_{\rm c}$ could lead to a brighter HB in the LMC, *provided that* the LMC GCs were *much* younger than their Galactic counterparts (so as to match their observed HB types). To put more stringent constraints on variations in the second-parameter candidates, analysis of the RR Lyrae pulsation properties is necessary.

3. Constraints from RR Lyrae pulsation properties

3.1. Mean pulsation periods

Light curves have been obtained by A. Walker for several GCs of the LMC. We have compiled data for the RR Lyrae-rich objects NGC 2257 (Walker 1989), NGC 1841 (Walker 1990), Reticulum (Walker 1992a), and NGC 1466 (Walker 1992c). This homogeneous database, supplemented by a few entries from Nemec et al. (1985) for NGC 2257, will be employed in the present discussion.

Mean pulsation periods for these GCs can be found in Table 1. Both mean "fundamentalized" periods (obtained by scaling the RRc periods as $\log P = \log P_{\rm c} + 0.13$) and mean RRab Lyrae periods are given, together with the number of variables employed in the analysis and the HB morphology. The [Fe/H] ratios were obtained from Walker 1992c or (in the cases of Reticulum and NGC 1841) from Suntzeff et al. 1992. Mean period shifts over all ab-type RR Lyraes, obtained at fixed effective temperature with respect to the lower envelope of the M3 distribution (cf. Fig. 1), are also displayed. For comparison purposes, also given are the corresponding values for the Galactic GCs M3 and M15, for which the mean periods were drawn from Castellani & Quarta 1987.

From Catelan's (1993) synthetic HB models for $Z = 4\times 10^{-4}$ and $\sigma_M = 0.02\, M_{\odot}$ (where σ_M is the mass dispersion on the HB), one finds that

$$\frac{{\rm d}\langle\log P_{\rm f}\rangle}{{\rm d}Y} \approx 1.6 \quad \text{and} \quad \frac{{\rm d}\langle\log L({\rm RR})\rangle}{{\rm d}Y} \approx 1.8. \qquad (1)$$

Table 1. Pulsation properties of LMC and Galactic GCs

	Cluster	[Fe/H]	$(B-R)/(B+V+R)$	$\langle\log P_{\rm f}\rangle$	$\langle\log P_{\rm ab}\rangle$	$\langle\Delta\log P(T_{\rm eff})\rangle$	$N_{\rm RR}$	$N_{\rm ab}$
LMC	Reticulum	−1.71	−0.04	−0.283	−0.260	+0.022	31	22
	NGC 2257	−1.8	+0.49	−0.291	−0.245	+0.041	31	15
	NGC 1466	−1.85	+0.40	−0.273	−0.234	+0.037	39	23
	NGC 1841	−2.11	+0.72	−0.209	−0.172	+0.072	22	17
Galaxy	M3	−1.66	+0.08	−0.276	−0.259	+0.025	179	148
	M15	−2.15	+0.72	−0.250	−0.188	+0.060	67	29

Uncertainties in such slope values are typically estimated to be of order 10%. In order to produce a $\Delta M_{\rm bol} = 0.3\,{\rm mag}$, this suggests that the helium abundance in the LMC should be larger than in the Galaxy by

$$\Delta Y \approx +0.07. \qquad (2)$$

According to Eqs. (1), this would imply an increase in the mean fundamentalized periods, in comparison with the Galactic values, by

$$\Delta\langle\log P_{\rm f}\rangle \approx +0.11. \qquad (3)$$

Table 1 does seem to rule out such a large difference in the mean periods.

Similar arguments apply to an increase in $M_{\rm c}$. For instance, from the Caputo et al. (1987) synthetic HB models for $Y_{\rm MS} = 0.20$ and $Z = 4\times 10^{-4}$, one finds that

$$\frac{{\rm d}\langle\log P_{\rm f}\rangle}{{\rm d}\Delta M_{\rm c}} \approx 2.3 \quad \text{and} \quad \frac{{\rm d}\langle\log L({\rm RR})\rangle}{{\rm d}\Delta M_{\rm c}} \approx 3.1. \qquad (4)$$

In order to produce a $\Delta M_{\rm bol} = 0.3\,{\rm mag}$, $M_{\rm c}({\rm LMC})$ should thus be larger than $M_{\rm c}({\rm Galaxy})$ by

$$\Delta M_{\rm c} \approx +0.04\,M_{\odot}. \qquad (5)$$

Equations (4) then show that this would imply an increase in the mean fundamentalized periods by

$$\Delta\langle\log P_{\rm f}\rangle \approx +0.09. \qquad (6)$$

This again appears to be ruled out by the data.

Catelan's (1993) synthetic HB models also suggest that

$$\frac{{\rm d}\langle\log L({\rm RR})\rangle}{{\rm d}\log Z} \approx -0.07. \qquad (7)$$

In order to produce a $\Delta M_{\rm bol} = 0.3\,{\rm mag}$, extrapolation of Eq. (7) toward very low metallicities suggests that the metal abundance in the LMC (for a given [Fe/H] ratio) should be smaller than in the Galaxy by

$$\Delta\log Z \approx -1.7. \qquad (8)$$

Irrespective of its impact upon RR Lyrae mean periods, such a change is clearly unrealistic.

3.2. Period shifts at fixed effective temperature

Another way to place constraints on the variations in second-parameter candidates is to analyze the relative positions of the cluster RR Lyraes on the period-effective temperature plane. Of course, the determination of temperatures for these stars is a rather problematic issue. Caputo & De Santis (1992) have advanced a method whereby the "mass-to-light ratio" of RRab Lyrae variables can be obtained in a reddening-independent way, from periods and blue amplitudes alone. From the period-mean density relation, in turn, this may be employed to derive RR Lyrae temperatures, and then to determine period shifts at fixed temperature with respect to the reference Galactic GC M3. Full details are

Fig. 1. $P - T_{\rm eff}$ plane for RR Lyrae variables in old LMC GCs. The mean period shifts obtained at fixed $T_{\rm eff}$ with respect to the lower envelope of the M3 distribution (bottom panel) are given, together with the cluster [Fe/H] ratios. The lower envelope of the M3 distribution is reproduced in each panel for clarity

given elsewhere (Catelan 1996), together with applications of the method to several Galactic globulars and samples of field stars.

The $\log P - \log T_{\rm eff}$ diagrams thus obtained for the studied LMC GCs are displayed in Fig. 1. The M3 distribution (from Catelan 1996) is reproduced in the bottom panel. The period shifts were measured with respect to the lower envelope of the M3 distribution (cf. Catelan 1996), which is reproduced in all panels for the sake of clarity.

From the definition of period shift, it follows that

$$\Delta \log P(T_{\rm eff}) = 0.84\, \Delta \log L(T_{\rm eff}) - 0.68\, \Delta \log M(T_{\rm eff}). \qquad (9)$$

Assuming, as a first approximation, the RR Lyrae masses at a given temperature in Galactic and LMC globulars to be the same, one finds that a shift in the RR Lyrae magnitudes by 0.3 mag should actually imply

$$\delta\Delta \log P(T_{\rm eff}) \approx +0.10. \qquad (10)$$

Both Fig. 1 and Table 1 clearly show that such a shift is not allowed for by the observational data.

A null LMC – Galaxy period shift could be produced if the RR Lyrae masses were higher, in the LMC, by $\delta\Delta \log M(T_{\rm eff}) \approx +0.15$ [cf. Eq. (9)]. For a mean mass $\langle M\rangle^{\rm RR}_{\rm Galaxy} \simeq 0.73\, M_{\odot}$ (as sugested by the Catelan 1993 synthetic HB models for $Y_{\rm MS} = 0.20$, $Z = 4 \times 10^{-4}$, $\sigma_M = 0.02\, M_{\odot}$ and not-too-blue HB types), this would actually demand RR Lyrae masses as high as $\langle M\rangle^{\rm RR}_{\rm LMC} \simeq 1.03\, M_{\odot}$ in the LMC – which is probably unrealistic.

4. Conclusions

The present analysis of the observational data for RR Lyrae variables in RR Lyrae-rich LMC GCs suggests that the discrepancy in the distance moduli of the LMC that are inferred from Cepheid and RR Lyrae variables cannot be entirely ascribed to variations in second-parameter candidates. This does *not* mean that such variations are not present, but rather that they would not be sufficient to reconcile the discrepant distance moduli. A satisfactory explanation of the problem has yet to be found.

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